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STUDY OF THE TEMPERATURE COEFFICIENTS OF AMORPHOUS AND POLYCRYSTALLINE SILICON PHOTOVOLTAIC MODULES UNDER REAL OPERATING CONDITIONS

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Abstract: The paper presents the results of study of the temperature coefficients of amorphous and polycrystalline silicon photovoltaic modules under real operating conditions in 10 kWp roof installed grid connected photovoltaic power plant in Technical University of Gabrovo, Bulgaria. Computer processing and rearranging of the monitoring data are carried out to separate the measurements into groups of approximately equal amounts of solar radiation. Graphical representation of the power, voltage and current as a function of the temperature at same level of solar radiation for the two types of modules are given. Change of power, voltage and current as a function of the temperature were obtained using linear regression functions. Operating temperature coefficients of amorphous and polycrystalline photovoltaic modules based on analytic functions have been established and compared with the nominal. Analyzes and conclusions of the research were made.

Keywords: amorphous and polycrystalline silicon photovoltaic modules, temperature coefficients, temperature dependence, linear regression analysis.

1. INTRODUCTION

The production of electricity through photovoltaic conversion has been one of the growing technologies in recent years. Qualitative design and operation of photovoltaic power plants requires good knowledge of the specific characteristics of the photovoltaic modules. Temperature dependence of the conversion efficiency of solar energy into electricity by the photovoltaic modules is usually given by producers as temperature coefficients on current, voltage and power under standard test conditions (STC): irradiation 1000 W/m², temperature 25°C, AM (Air Mass) 1.5. Actual operating conditions are different from the STC, which leads to a change of temperature coefficients. The character of this change varies for different technologies of photovoltaic modules. Many scientists have undertaken research on changes of temperature coefficients [1−6].

The present work represents the study of the temperature coefficients of amorphous and polycrystalline silicon photovoltaic modules under real operating conditions in 10 kWp grid connected photovoltaic power plant in Technical University of Gabrovo, Bulgaria – Figure 1 [7].

Figure 1. Grid connected photovoltaic power plant on the roof of the Rectorate of Technical University of Gabrovo

The photovoltaic power plant was installed on the roof of the Rectorate building in 2005. It consists of three subsystems. The first and the second subsystems with single installed power of 3.42 kWp are identical, each containing 12 polycrystalline silicon PV modules, type ASE-250 DG-FT/MC. The third subsystem with power of 3.22 kWp is built from a field of 100 amorphous silicon PV modules

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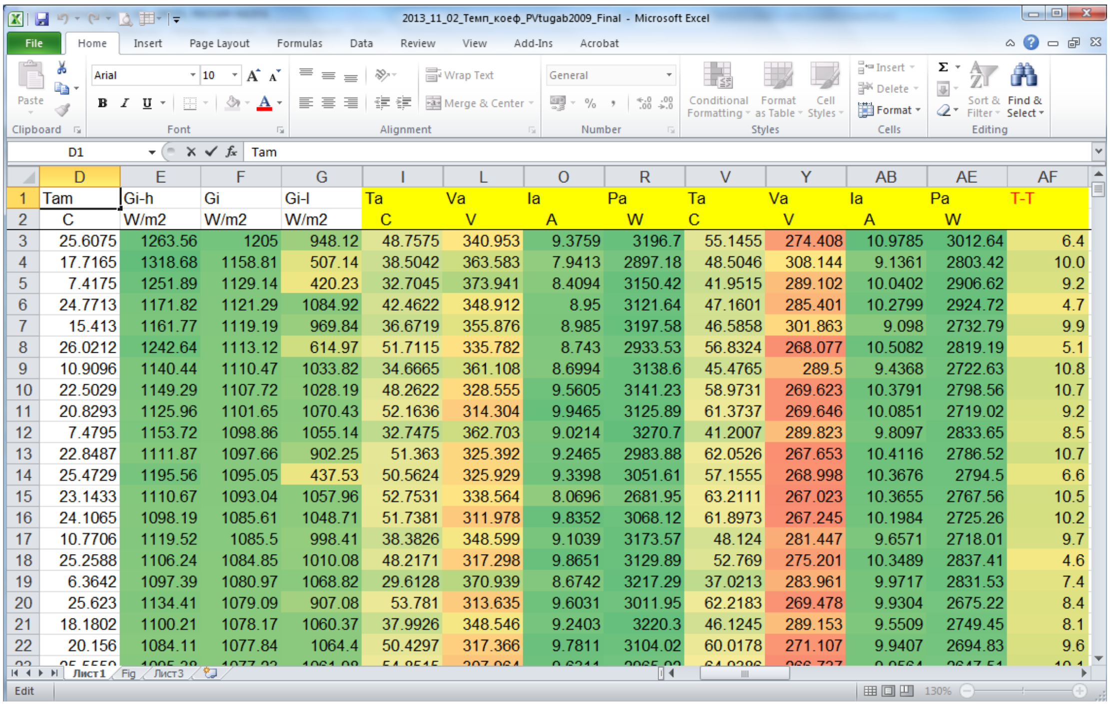
type ASE-F 32/12. A monitoring system performs regular measurement and storage of the following data [8]: global solar radiation; solar radiation in the plane of PV modules; temperature of the two types of PV modules; temperature of the silicon reference cell; ambient temperature; current, voltage and power of the DC side of three subsystems; DC and AC energy produced by three subsystems; total energy produced.

2. STUDY OF TEMPERATURE COEFFICIENTS

The main task of the present study is to investigate the change of temperature coefficients of two of the most common technologies for photovoltaic modules - polycrystalline and amorphous silicon at different levels of solar radiation and module temperatures in real working conditions of roof installed grid connected photovoltaic power plant.

The first stage of the study is rearrangement of the measured and collected data using the monitoring system of the working grid connected photovoltaic power plant with amorphous (a-Si) and polycrystalline (p-Si) silicon photovoltaic modules subsystems. The monitoring system keeps records of minimum, maximum and average values of each measured parameter for each 10-minute period of operation of the electrical power plant. The data on one calendar year is processed using the integrated functions of Microsoft Excel – Figure 2.



	D	E	F	G	I	L	O	R	V	Y	AB	AE	AF
1	Tam	Gi-h	Gi	Gi-I	Ta	Va	Ia	Pa	Ta	Va	Ia	Pa	T-T
2	C	W/m2	W/m2	W/m2	C	V	A	W	C	V	A	W	
3	25.6075	1263.56	1205	948.12	48.7575	340.953	9.3759	3196.7	55.1455	274.408	10.9785	3012.64	6.4
4	17.7165	1318.68	1158.81	507.14	38.5042	363.583	7.9413	2897.18	48.5046	308.144	9.1361	2803.42	10.0
5	7.4175	1251.89	1129.14	420.23	32.7045	373.941	8.4094	3150.42	41.9515	289.102	10.0402	2906.62	9.2
6	24.7713	1171.82	1121.29	1084.92	42.4622	348.912	8.95	3121.64	47.1601	285.401	10.2799	2924.72	4.7
7	15.413	1161.77	1119.19	969.84	36.6719	355.876	8.985	3197.58	46.5858	301.863	9.098	2732.79	9.9
8	26.0212	1242.64	1113.12	614.97	51.7115	335.782	8.743	2933.53	56.8324	268.077	10.5082	2819.19	5.1
9	10.9096	1140.44	1110.47	1033.82	34.6665	361.108	8.6994	3138.6	45.4765	289.5	9.4368	2722.63	10.8
10	22.5029	1149.29	1107.72	1028.19	48.2622	328.555	9.5605	3141.23	58.9731	269.623	10.3791	2798.56	10.7
11	20.8293	1125.96	1101.65	1070.43	52.1636	314.304	9.9465	3125.89	61.3737	269.646	10.0851	2719.02	9.2
12	7.4795	1153.72	1098.86	1055.14	32.7475	362.703	9.0214	3270.7	41.2007	289.823	9.8097	2833.65	8.5
13	22.8487	1111.87	1097.66	902.25	51.363	325.392	9.2465	2983.88	62.0526	267.653	10.4116	2786.52	10.7
14	25.4729	1195.56	1095.05	437.53	50.5624	325.929	9.3398	3051.61	57.1555	268.998	10.3676	2794.5	6.6
15	23.1433	1110.67	1093.04	1057.96	52.7531	338.564	8.0696	2681.95	63.2111	267.023	10.3655	2767.56	10.5
16	24.1065	1098.19	1085.61	1048.71	51.7381	311.978	9.8352	3068.12	61.8973	267.245	10.1984	2725.26	10.2
17	10.7706	1119.52	1085.5	998.41	38.3826	348.599	9.1039	3173.57	48.124	281.447	9.6571	2718.01	9.7
18	25.2588	1106.24	1084.85	1010.08	48.2171	317.298	9.8651	3129.89	52.769	275.201	10.3489	2837.41	4.6
19	6.3642	1097.39	1080.97	1068.82	29.6128	370.939	8.6742	3217.29	37.0213	283.961	9.9717	2831.53	7.4
20	25.623	1134.41	1079.09	907.08	53.781	313.635	9.6031	3011.95	62.2183	269.478	9.9304	2675.22	8.4
21	18.1802	1100.21	1078.17	1060.37	37.9926	348.546	9.2403	3220.3	46.1245	289.153	9.5509	2749.45	8.1
22	20.156	1084.11	1077.84	1064.4	50.4297	317.366	9.7811	3104.02	60.0178	271.107	9.9407	2694.83	9.6

Figure 2. Processing and rearrangement of the collected data in Microsoft Excel

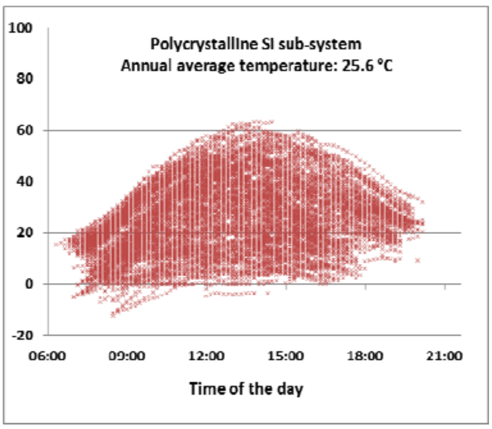


Figure 3. Polycrystalline PV modules temperature change during the time of the day

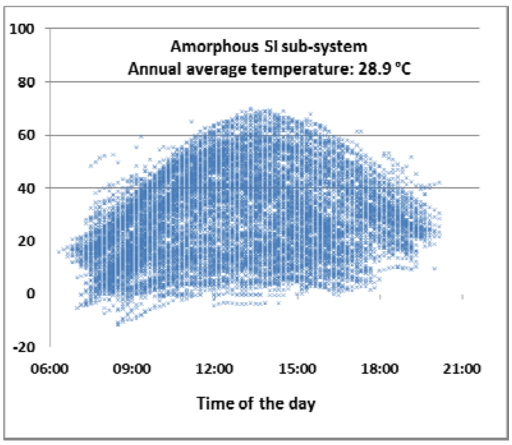


Figure 4. Amorphous PV modules temperature change during the time of the day

The temperature of the photovoltaic modules is measured with platinum thermo-resistors Pt100 fastened with heat conductive paste on their back side. Temperature change during the time of the day for polycrystalline and amorphous photovoltaic modules are shown in Figure 3 and Figure 4 respectively. Figure 5 shows the calculated conversion efficiency of solar energy into electrical depending on PV modules temperature.

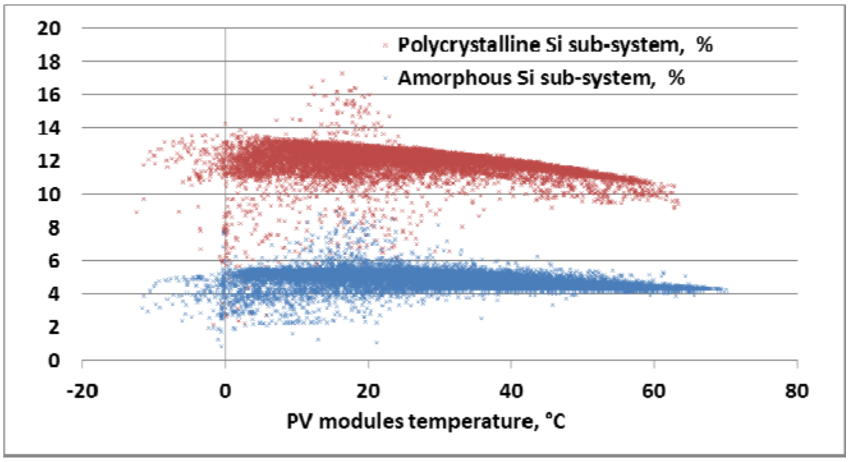


Figure 5. Conversion efficiency of solar energy into electrical depending on PV modules temperature

The one year data is distributed in 10 groups with similar solar radiation level Gi with difference up to 100 W/m^2 in the following way: the first group named "Gi ≈ 1000 W/m^2" contains all records with the measured values of Gi from 1050 to 950 W/m^2, in the group named "Gi ≈ 900 W/m^2" there are all records with the measured value of Gi from 950 to 850 W/m^2, etc. – Table 1. The percentage of annual measurements that fall into each group with a given range of solar radiation is also shown in the table.

Table 1. Measured data distribution in the groups with similar solar radiation level

Solar radiation group, W/m^2	1000	900	800	700	600	500	400	300	200	100
Range of measured solar radiation, W/m^2	1050 to 950	950 to 850	850 to 750	750 to 650	650 to 550	550 to 450	450 to 350	350 to 250	250 to 150	150 to 50
Percentage of the annual measurements, %	6.2	8.2	8.0	7.3	7.0	7.0	8.3	9.9	13.7	24.5

Graphical representation of the power, voltage and current as a function of the temperature at the same level of solar radiation for the amorphous and polycrystalline photovoltaic modules are made separately for 10 different levels of solar radiation Gi. Using linear regression functions, the trends of change of power *Pa*, voltage *Va* and current *Ia* as a function of the temperature *Ta* were obtained. Figures 6, 7, 8, 9, 10 and 11 show a part of graphical dependencies for levels of solar radiation Gi = 1000 W/m^2, Gi = 500 W/m^2 and Gi = 100 W/m^2 for the two sub-systems with tested types of photovoltaic modules.

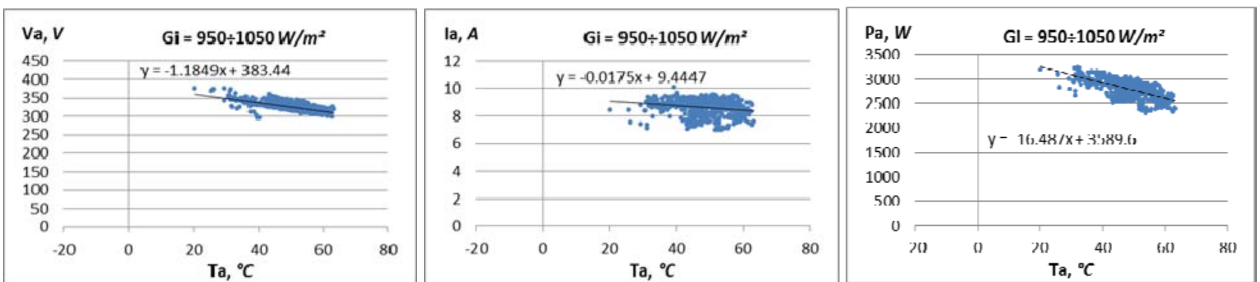


Figure 6. Va=f(Ta), Ia=f(Ta) and Pa=f(Ta) under Gi≈1000W/m^2 for sub-system with a-Si PV modules

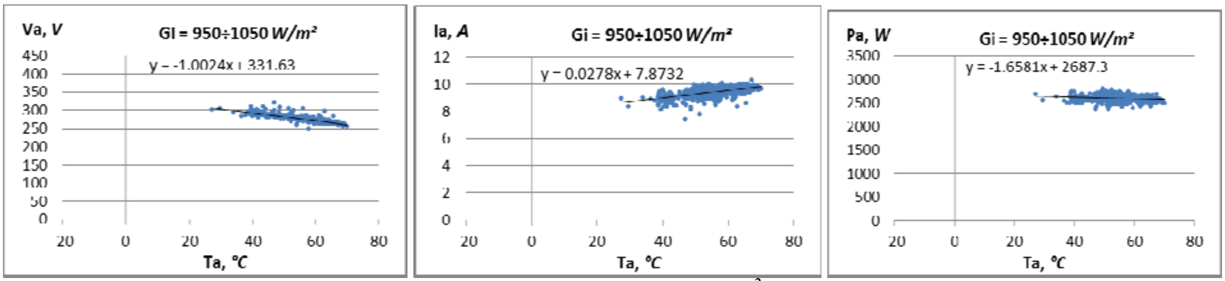


Figure 7. Va=f(Ta), Ia=f(Ta) and Pa=f(Ta) under Gi≈1000W/m² for sub-system with p-Si PV modules

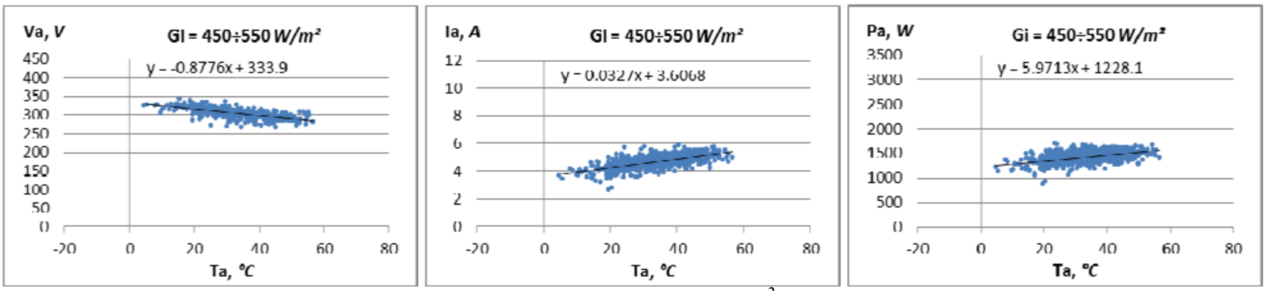


Figure 8. Va=f(Ta), Ia=f(Ta) and Pa=f(Ta) under Gi≈500W/m² for sub-system with a-Si PV modules

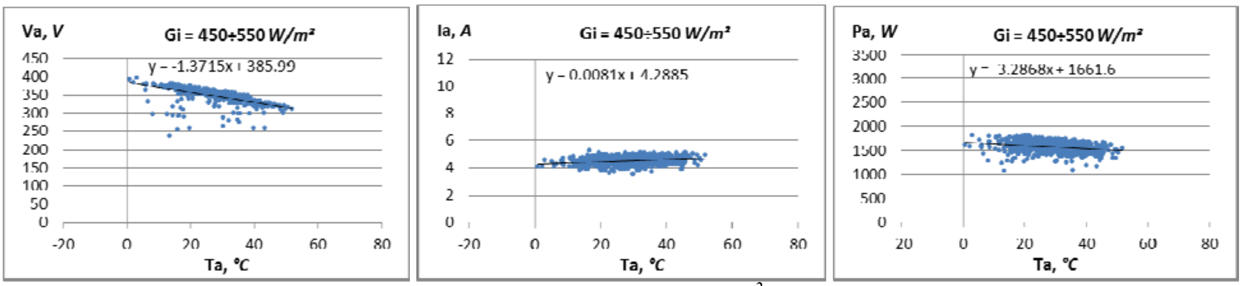


Figure 9. Va=f(Ta), Ia=f(Ta) and Pa=f(Ta) under Gi≈500W/m² for sub-system with p-Si PV modules

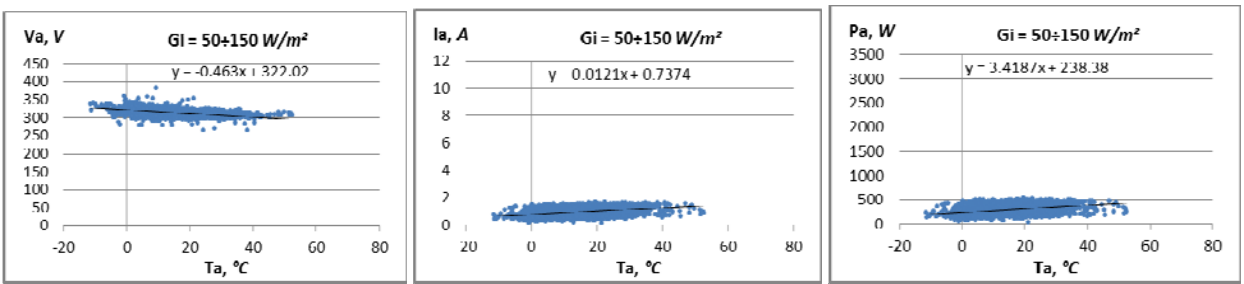


Figure 10. Va=f(Ta), Ia=f(Ta) and Pa=f(Ta) under Gi≈100W/m² for sub-system with a-Si PV modules

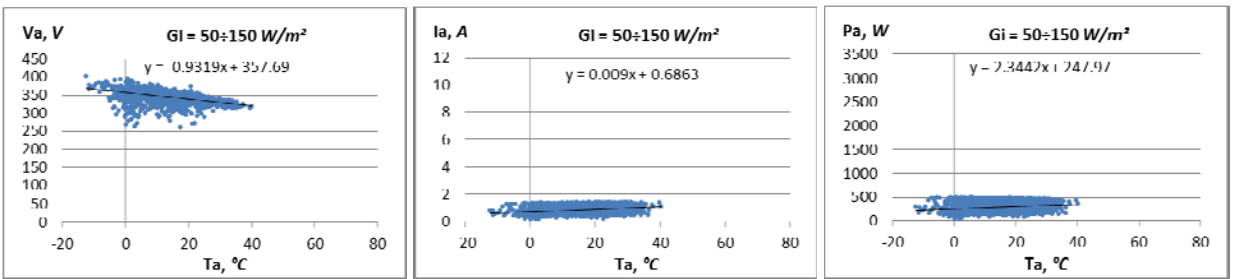


Figure 11. Va=f(Ta), Ia=f(Ta) and Pa=f(Ta) under Gi≈100W/m² for sub-system with p-Si PV modules

Based on linear regression, analytic functions shown in figures are established for operating temperature coefficients of amorphous and polycrystalline photovoltaic modules. Derived current α, voltage β and power γ temperature coefficients under real operating conditions in absolute measurement units for all 10 solar radiation levels are given in Table 2.

Variation of the current α, voltage β and power γ temperature coefficients in absolute measurement units depending on the level of solar radiation is shown graphically in Figure 9.

Table 2. Derived current α, voltage β and power γ temperature coefficients in absolute measurement units

Solar radiation [W/m^2]	Sub-system with polycrystalline silicon PV modules			Sub-system with amorphous silicon PV modules		
	$\alpha_{p\text{-}Si}$, [A/°C]	$\beta_{p\text{-}Si}$, [V/°C]	$\gamma_{p\text{-}Si}$, [W/°C]	$\alpha_{a\text{-}Si}$, [A/°C]	$\beta_{a\text{-}Si}$, [V/°C]	$\gamma_{a\text{-}Si}$, [W/°C]
1000 ±50	-0.0175	-1.1849	-16.487	0.0278	-1.0024	-1.6581
900 ±50	0.0042	-1.4833	-10.720	0.0362	-0.9848	1.8509
800 ±50	0.0106	-1.5162	-7.3251	0.0396	-0.9992	4.1034
700 ±50	0.0111	-1.6124	-6.2914	0.0380	-0.9827	4.7536
600 ±50	0.0096	-1.4900	-4.6739	0.0370	-0.9837	5.6600
500 ±50	0.0081	-1.3715	-3.2868	0.0327	-0.8776	5.9713
400 ±50	0.0065	-1.3240	-2.5727	0.0250	-0.8067	4.8018
300 ±50	0.0063	-1.2820	-1.3758	0.0206	-0.7951	4.2784
200 ±50	0.0064	-1.1110	0.2216	0.0154	-0.6629	3.6307
100 ±50	0.0090	-0.9319	2.3442	0.0121	-0.4630	3.4187

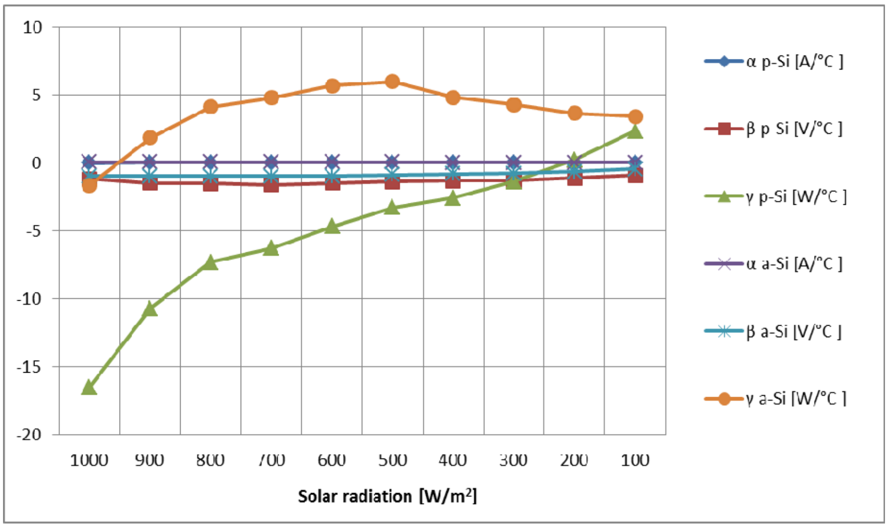


Figure 9. Variation of the current, voltage and power temperature coefficients in absolute measurement units depending on the level of solar radiation

Table 3. Calculated current α, voltage β and power γ temperature coefficients in % / °C

Solar radiation [W/m^2]	Sub-system with polycrystalline silicon PV modules			Sub-system with amorphous silicon PV modules		
	$\alpha_{p\text{-}Si}$, [%/°C]	$\beta_{p\text{-}Si}$, [%/°C]	$\gamma_{p\text{-}Si}$, [%/°C]	$\alpha_{a\text{-}Si}$, [%/°C]	$\beta_{a\text{-}Si}$, [%/°C]	$\gamma_{a\text{-}Si}$, [%/°C]
Nominal at STC	0.10	-0.38	-0.47	0.08	-0.33	-0.20
1000 ±50	-0.183	-0.331	-0.482	0.290	-0.298	-0.515
900 ±50	0.044	-0.414	-0.313	0.377	-0.293	0.575
800 ±50	0.111	-0.423	-0.214	0.413	-0.297	1.274
700 ±50	0.116	-0.450	-0.184	0.396	-0.292	1.476
600 ±50	0.101	-0.416	-0.137	0.385	-0.293	1.758
500 ±50	0.085	-0.383	-0.096	0.341	-0.261	1.854
400 ±50	0.068	-0.370	-0.075	0.260	-0.240	1.491
300 ±50	0.066	-0.358	-0.040	0.215	-0.237	1.329
200 ±50	0.067	-0.310	0.006	0.160	-0.197	1.128
100 ±50	0.094	-0.260	0.069	0.126	-0.138	1.062

For a more correct analysis and in order for the obtained values of α, β and γ to be compared with the nominal values given by the producers of photovoltaic modules, temperature coefficients are converted into relative units: % / °C. The calculated values of temperature coefficients in real working conditions and the nominal values at STC in % / °C are given in Table 3.

Graphical presentation of the variation of the temperature coefficients in % / °C depending on the level of solar radiation is shown in Figure 10.

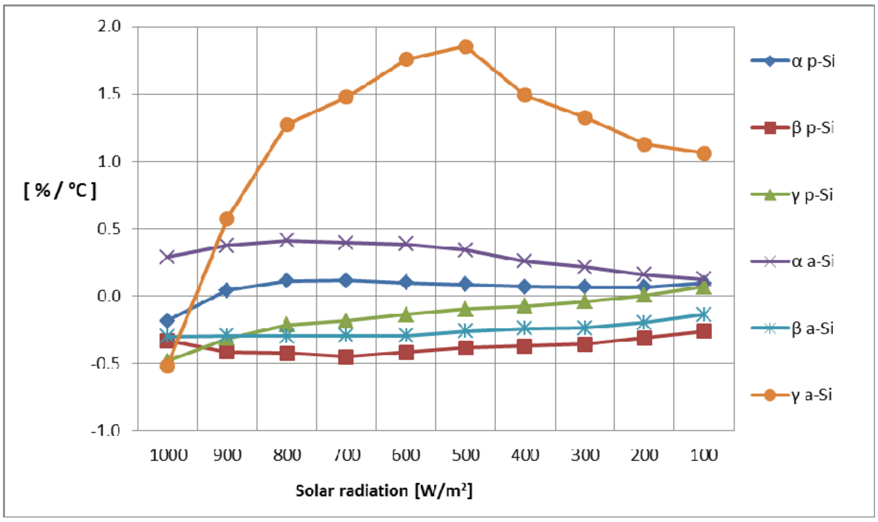


Figure 10. Variation of the temperature coefficients in % / °C depending on the level of solar radiation

3. ANALYSIS

During analysis, the studies should take into account that they are made under real operating conditions and results depend not only on the physical characteristics of PV modules, but also on the weather conditions at the given location, type of installation of the modules and the influence of the parameters and devices used in electrical part of the photovoltaic power plant. The inverters used for sub-systems with polycrystalline and amorphous photovoltaic modules are exactly the same, but because of different volt-ampere characteristics of the two technology modules, their maximum power point trackers work with different electrical parameters.

The analysis of the results of the present studies to investigate the change of temperature coefficients of polycrystalline and amorphous silicon photovoltaic modules at different levels of solar radiation and module temperatures in real working conditions of roof installed grid connected photovoltaic power plant located in the center of Bulgaria, leads to the following discussion:

− The working temperature during the time of the day changes from –12.4 °C to +63.3 °C with the annual average value of 25.6 °C for polycrystalline silicon PV modules (Figure 3) and from –11.5 °C to +70.1 °C with annual average value of 28.9 °C amorphous silicon PV modules (Figure 4);

− Obtained operating temperature coefficients have a significant change with a different trend for the two technologies of photovoltaic modules depending on the level of solar radiation. For polycrystalline silicon PV modules, power temperature coefficient at Gi=1000W/m^2 is negative $\gamma_{p\text{-}Si}$= –0.482 %/°C and very close to nominal at STC $\gamma_{p\text{-}Si\ STS}$= – 0,47 %/°C, despite the bigger differences in current and voltage temperature coefficients (Table 3 and Figure 10). With a decrease in the level of solar radiation, $\gamma_{p\text{-}Si}$ is amended to zero and positive at levels below Gi=200 W/m^2, as on the levels below Gi=800 W/m^2 the trend is close to linear. (Tables 2 and 3 and Figures 9 and 10). For amorphous silicon PV modules, power temperature coefficient at Gi=1000W/m^2 is negative $\gamma_{a\text{-}Si}$= –0.515 %/°C and bigger in absolute value than the nominal at STC $\gamma_{a\text{-}Si\ STC}$= – 0.20 %/°C, as the difference is caused mainly by the bigger current temperature coefficient $\alpha_{a\text{-}Si}$ (Table 3 and Figure 10). With a decrease in the level of solar radiation below Gi=900 W/m^2, $\gamma_{a\text{-}Si}$ rapidly becomes positive and increases significantly in absolute value, as the trend is not linear. (Tables 2 and 3 and Figures 9 and 10). The maximum value of $\gamma_{a\text{-}Si}$= +1.854 %/°C is obtained at the level of solar radiation Gi=500 W/m^2.

4. CONCLUSIONS

After the analysis, it is established that in real operating conditions polycrystalline silicon PV modules work 62 % of the time with negative power temperature coefficient, lower than the nominal at STC as an absolute value, whereas amorphous silicon PV modules work 94 % of the time with relatively big positive power temperature coefficient, although their nominal power temperature coefficient at STC is negative (Table 1 and 3, Figure 10).

For polycrystalline PV modules about 20% reduction of calculated conversion efficiency of solar energy into electrical is obtained when increasing temperature of the modules from −10 °C to +60 °C, while for the amorphous PV modules the change is negligible (Figure 5).

These final conclusions could serve to increase the efficiency of the photovoltaic power plants during their design by optimizing the selection of a suitable PV module technology for a given location and type of installation of photovoltaic modules in terms of opportunities to influence their temperature control.

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ИСПИТИВАЊЕ ТЕМПЕРАТУРНИХ КОЕФИЦИЈЕНАТА АМОРФНИХ И ПОЛИКРИСТАЛНИХ СИЛИКОНСКИХ ФОТОНАПОНСКИХ МОДУЛА У СТВАРНИМ РАДНИМ УСЛОВИМА

Сажетак: У раду су представљени резултати иситивања температурних коефицијената аморфних и поликристалних силиконских фотонапонских модула у стварним радним условима у фотонапонској електрани од 10 kWp, мрежно повезаној и инсталираној на крову Техничког универзитета у Габрову, Бугарска. Компјутерска обрада и прерасподјела података праћења спроведени су да би се раздвојила мјерења у групе приближно једнаких износа сунчевог зрачења. Дат је графички приказ снаге, напона и струје као функције температуре на истом нивоу сунчевог зрачења за двије врсте модула. Промјена снаге, напона и струје као функција температуре добијена је употребом линеарних регресионих функција. Установљени су коефицијенти радне температуре аморфних и поликристалних фотонапонских модула на основу аналитичких функција и упоређени с номиналним. Извршена је анализа и донешени закључци истраживања.

Кључне ријечи: аморфни и поликристални силиконски фотонапонски модули, температурни коефицијенти, температурна зависност, линеарна регресиона анализа.